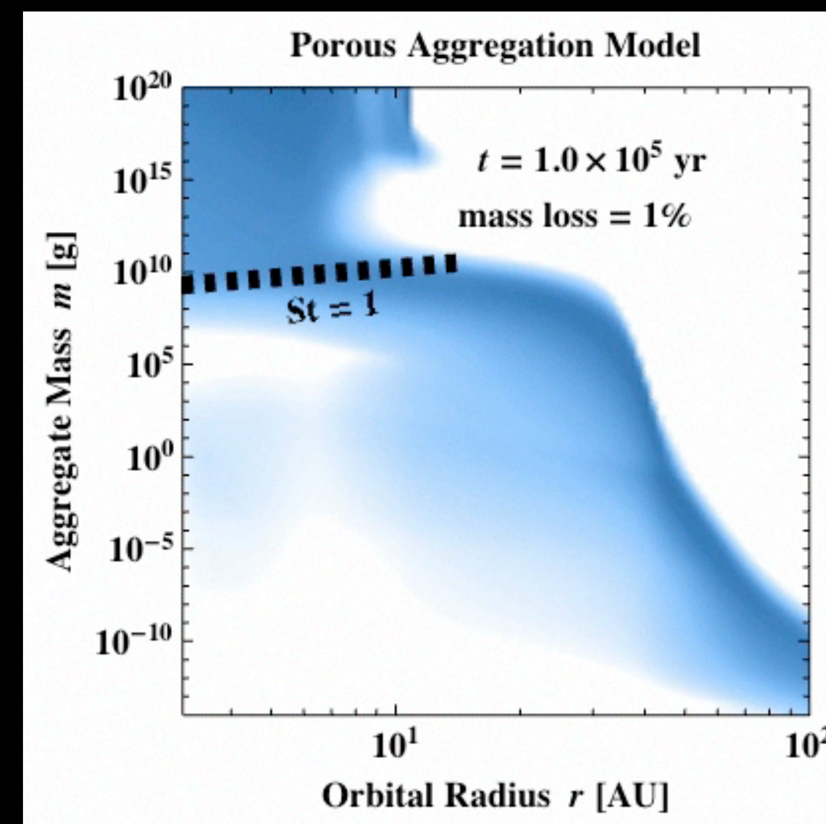
Rapid Coagulation of Porous Dust Aggregates Outside the Snow Line

A Pathway to Successful Icy Planetesimal Formation



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ANIMATION: N-body Collision Experiments by Suyama et al. (2008)

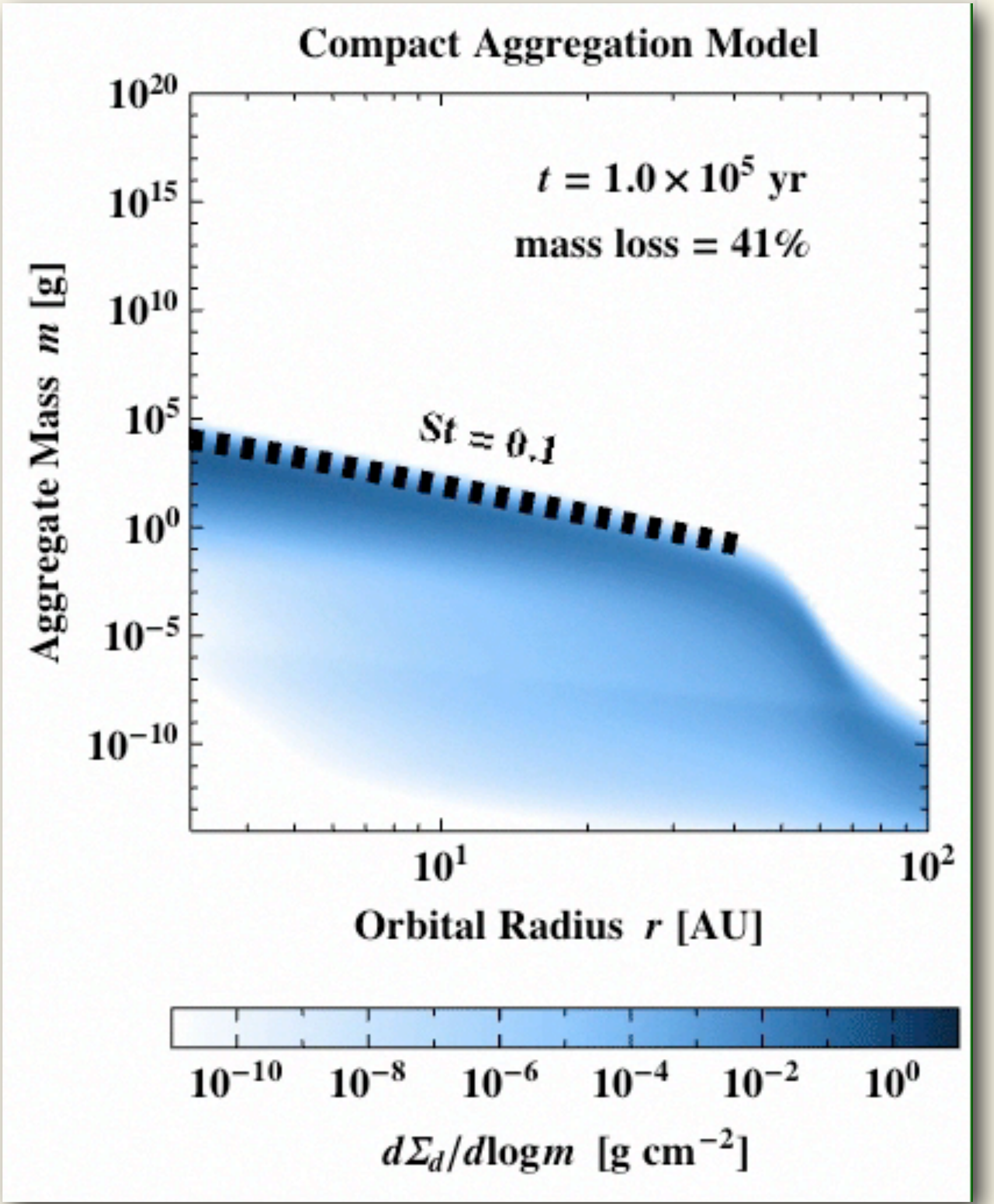
The Radial Drift Barrier against Dust Growth

Headwind ➡ Angular mom. loss
➡Inward drift

$$v_{\rm drift} \approx 50\ {\rm m\ s^{-1}}\ \frac{2{\rm St}}{1+{\rm St}^2}$$

St = $\Omega t_{\rm stop}$: Stokes number

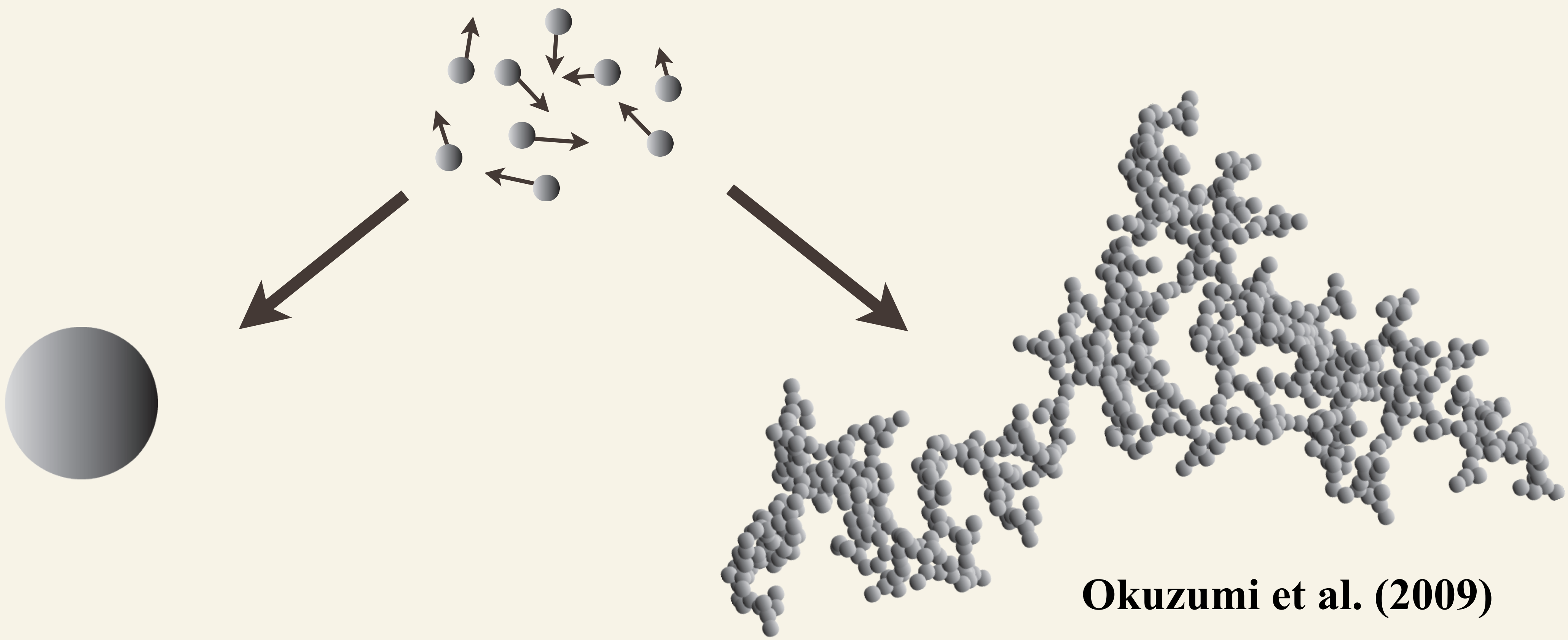
(Adachi et al. 76; Weidenschilling 77)



At St~1, inward drift is faster than collisional growth (Brauer et al. 2008)

➡ A barrier against planetesimal formation

Beyond the Compact Grain Paradigm



Okuzumi et al. (2009)

Compact Sphere

- Filling factor ~ 1
- High St
- The "classic" model

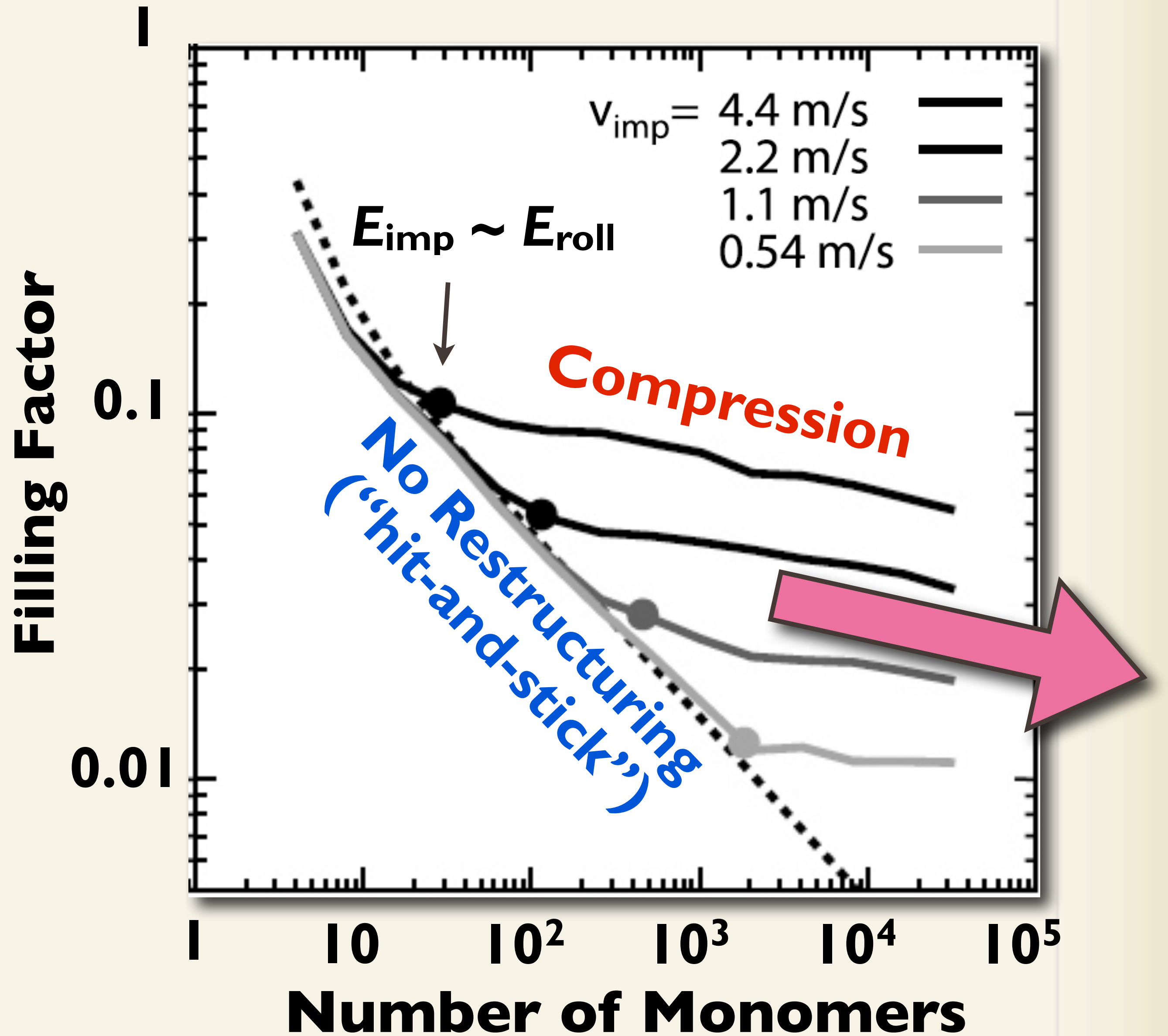
Porous Aggregate

- Filling factor ≪ 1
- Low St
- Ormel et al. '07; Okuzumi et al. '09; Zsom et al. '10, '11

Collisional Compaction is Inefficient

Suyama, Wada, & Tanaka (2008)

Suyama, Wada, Tanaka, & Okuzumi (2012)



The filling factor can be << 0.1
even after the onset of collisional compression!

Dust Growth Outside the Snow Line

Coagulation + Radial Drift + Porosity Evolution

- Coagulation + drift: Global bin method (Brauer et al. 2008)
- Porosity: Compression recipe based on *N*-body experiments (Suyama et al. 2012)

Outside the Snow Line

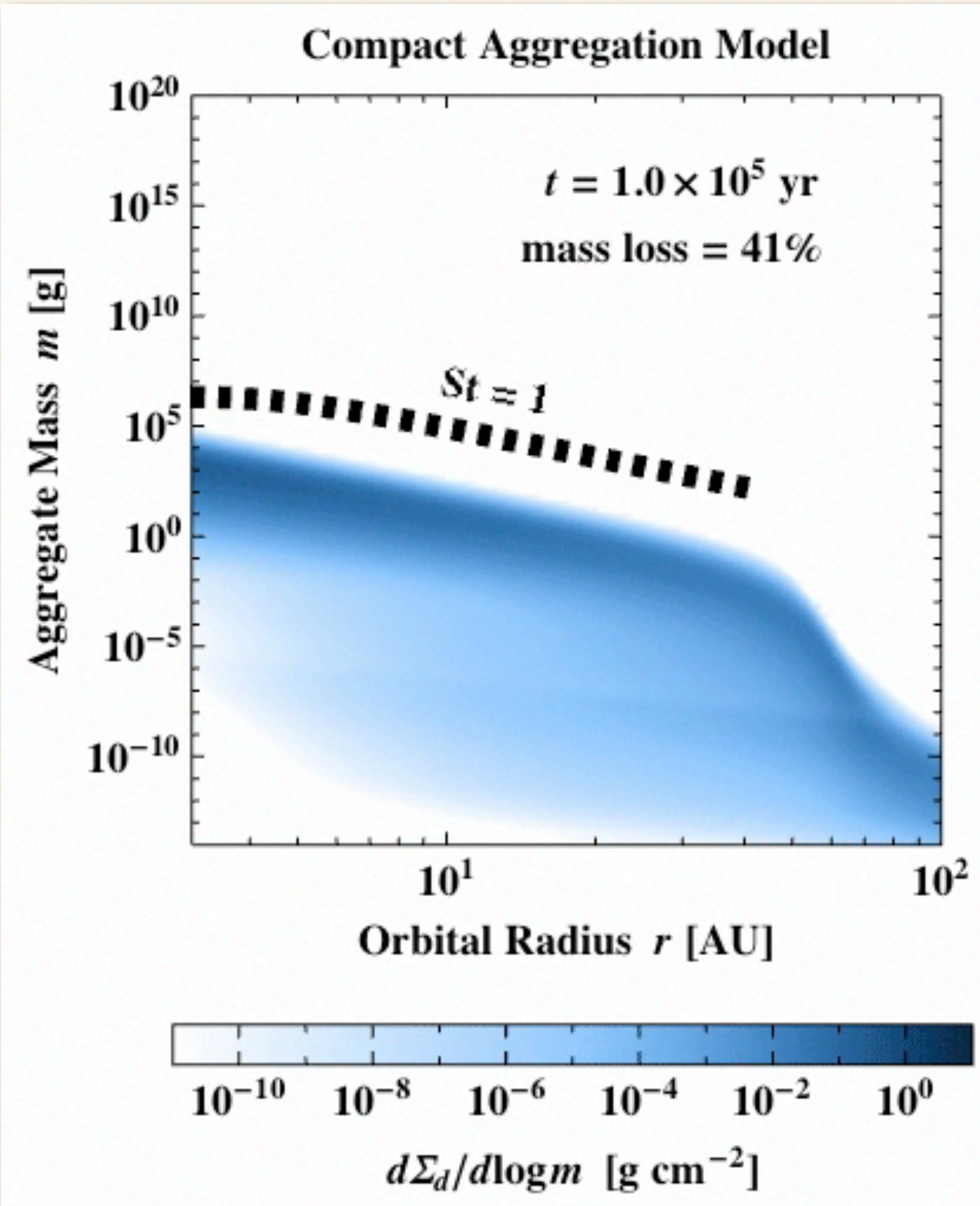
- Ice mantle → High sticking efficiency
- Disruption velocity v_{disr} ~ **40-70 m/s** **(Wada et al. 2009)** $\gtrsim$ **Collision velocity**

➡ **We neglect fragmentation**

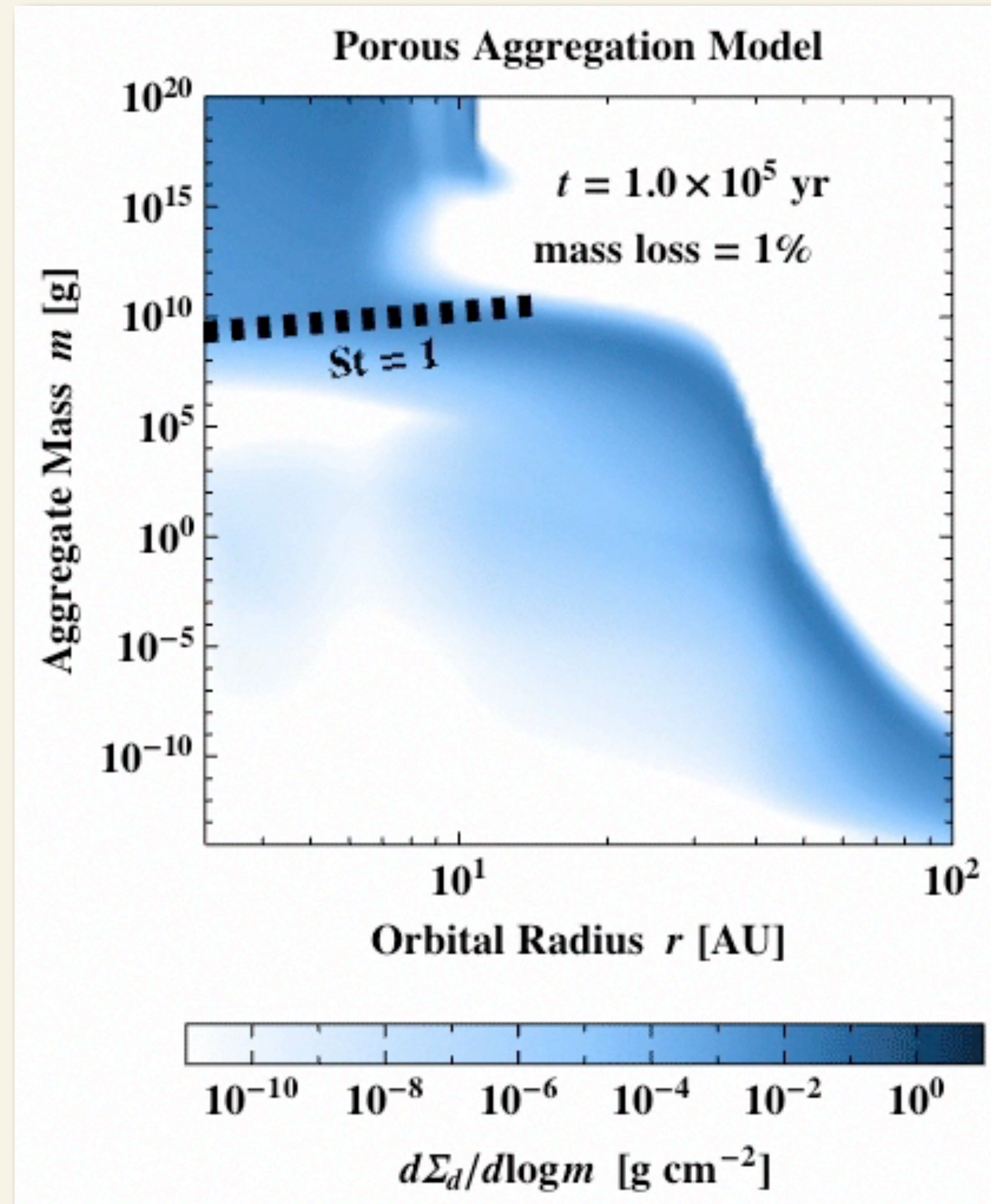
- Minimum-mass solar nebula (Hayashi et al. 81)
- Turbulence $\alpha = 10^{-3}$
- Dust-to-gas mass ratio = 0.01
- $T = 280(r/\mathrm{AU})^{-1/2}$ K ➡ $r_{snow} \approx 3$AU

Results: Global Evolution

Compact

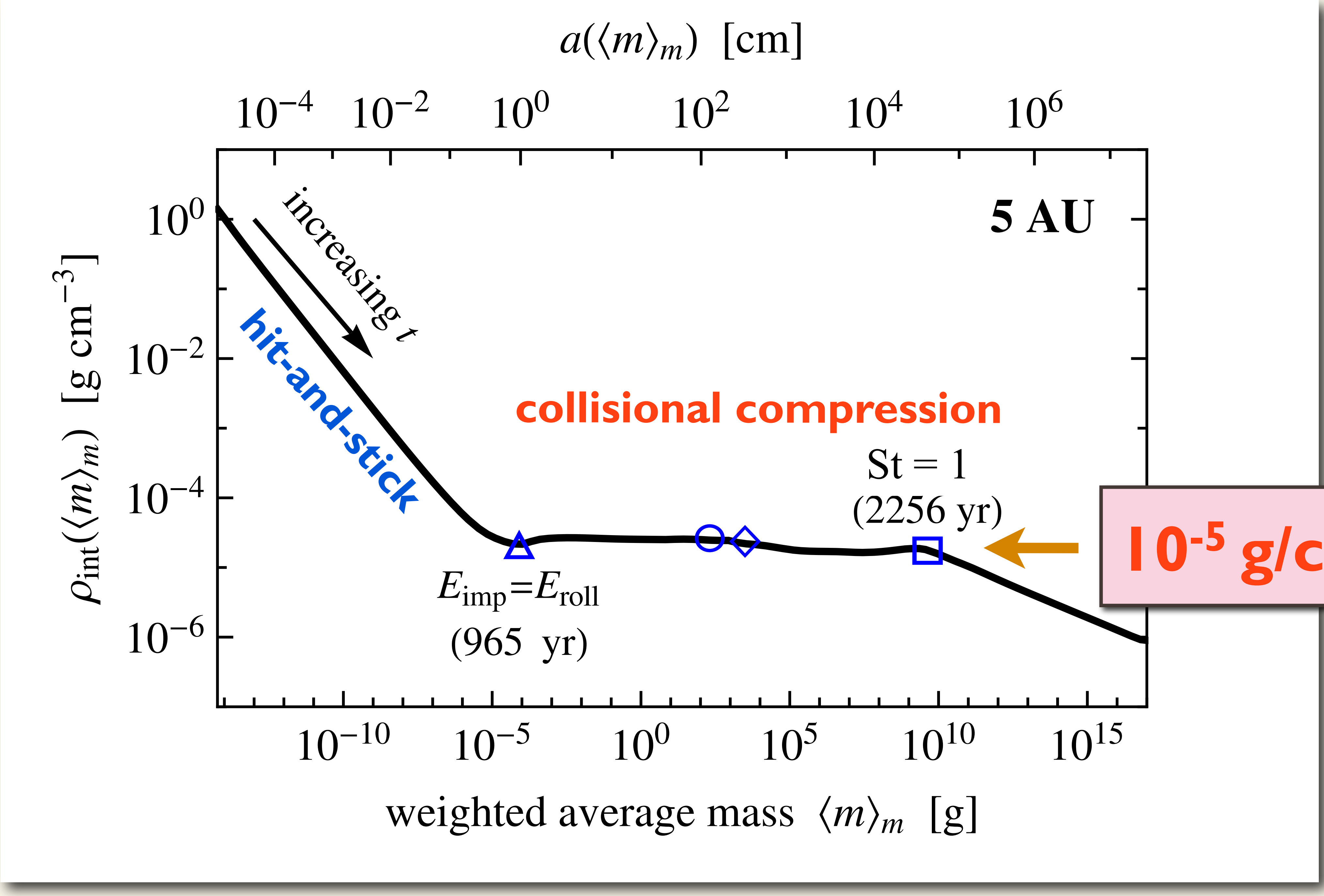


Porous



(Okuzumi et al. 2012)

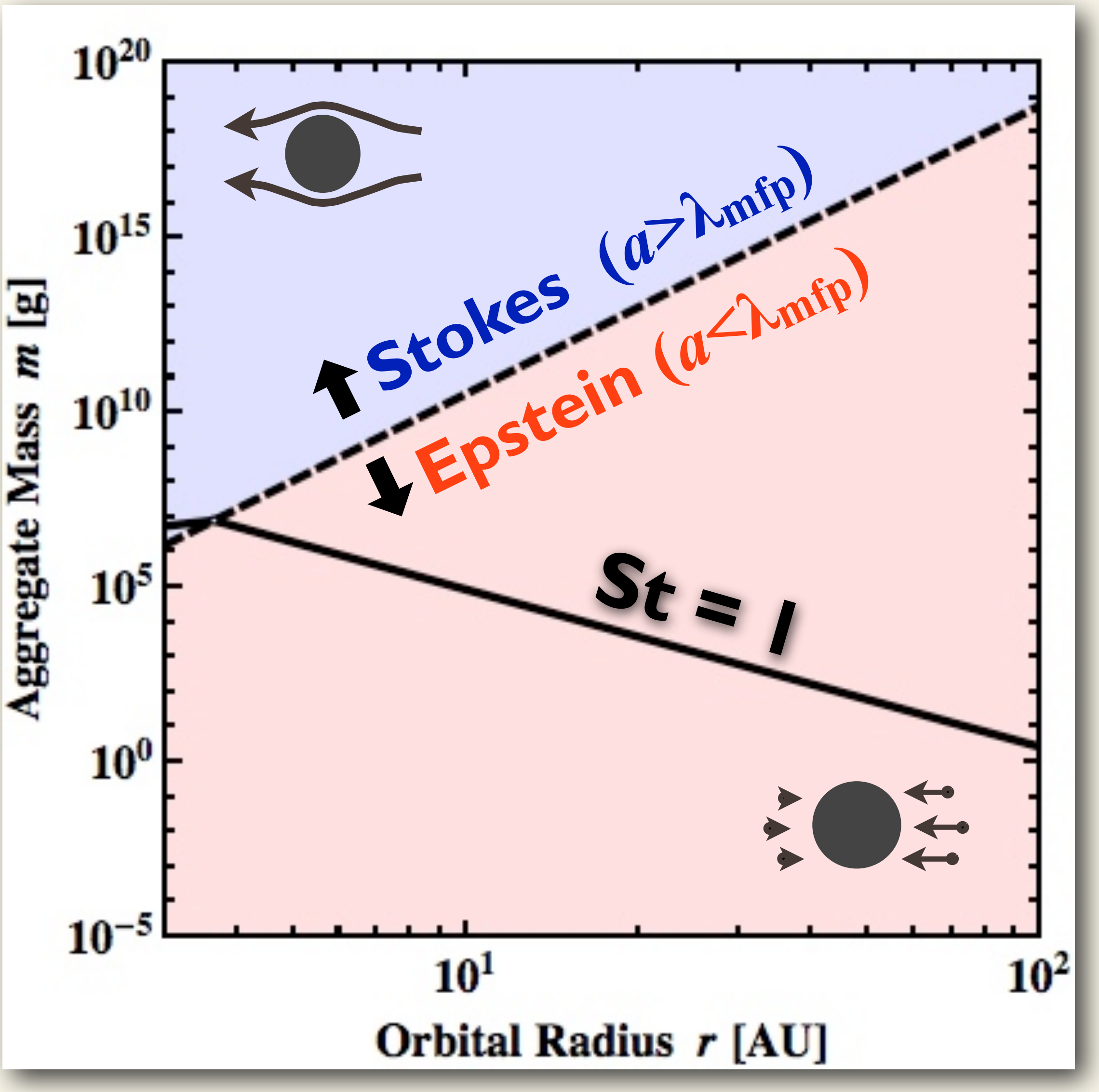
Evolution of the Aggregate Internal Density



10^{-5} g/cm^3 !!

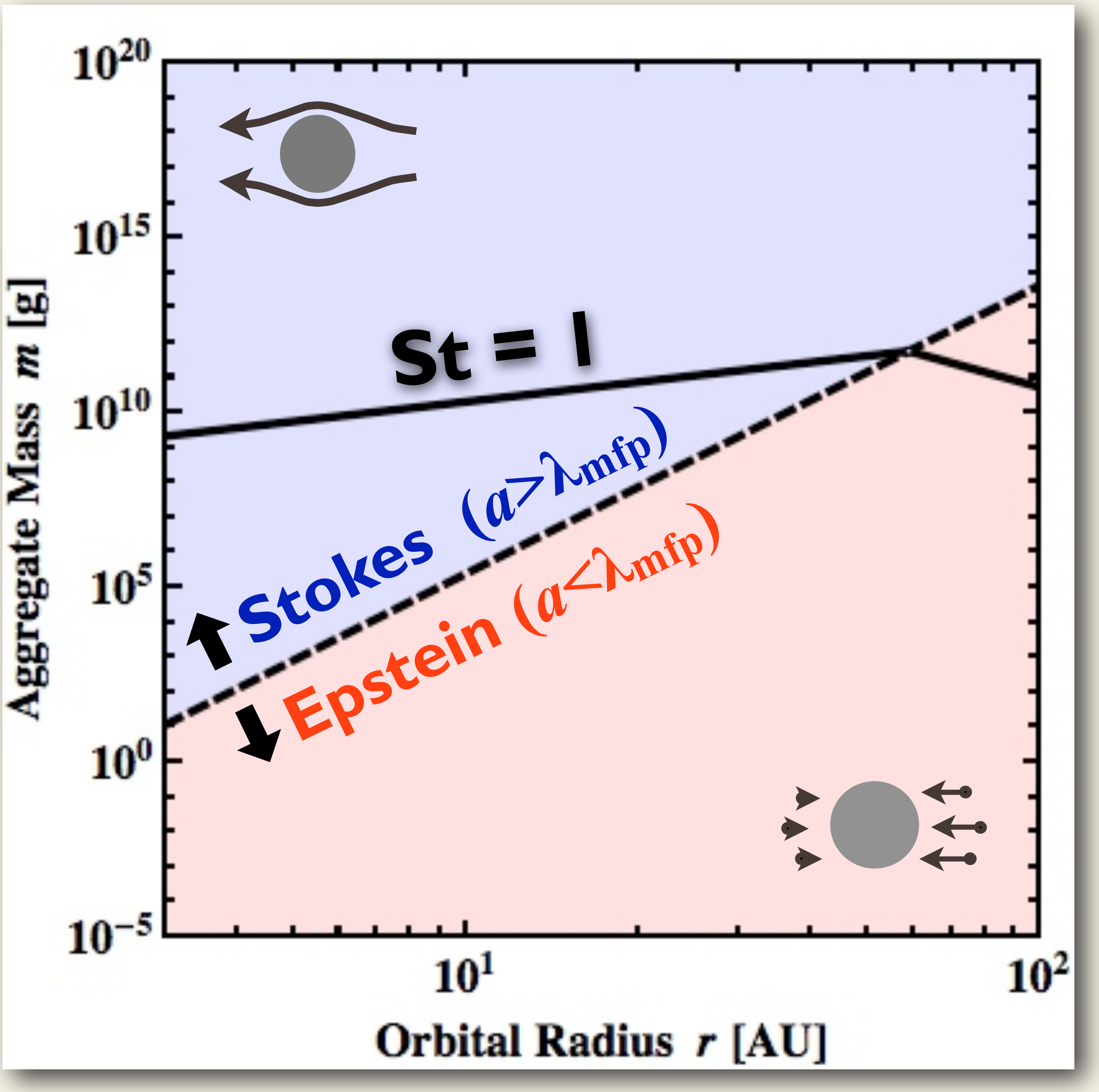
Higher Porosity ➡ Wider Stokes Regime

Compact (ϕ=100%)



St = 1 in the Epstein regime

Fluffy (ϕ=10^{-5})



St = 1 in the Stokes regime

"Stokes Acceleration"

Growth timescale $t_{\rm grow} \equiv \left(\frac{d\ln m}{dt}\right)^{-1} = \frac{m}{\rho_d \sigma \Delta v}$

- **In the Epstein Regime (*a* « $\lambda_{\rm mfp}$):**

$$t_{\rm grow} \sim 100 \left(\frac{\Sigma_g/\Sigma_d}{100}\right)\Omega^{-1}$$

(Takeuchi & Lin 05; Brauer et al. 08; Birnstiel et al. 12)

This is *not* short enough to overcome the drift barrier! (see Brauer et al. 08)

- **However, in the *Stokes* Regime (*a* » $\lambda_{\rm mfp}$):**

$$t_{\rm grow} \sim 100 \left(\frac{\lambda_{\rm mfp}}{a}\right)\left(\frac{\Sigma_g/\Sigma_d}{100}\right)\Omega^{-1}$$

(Okuzumi et al. 12)

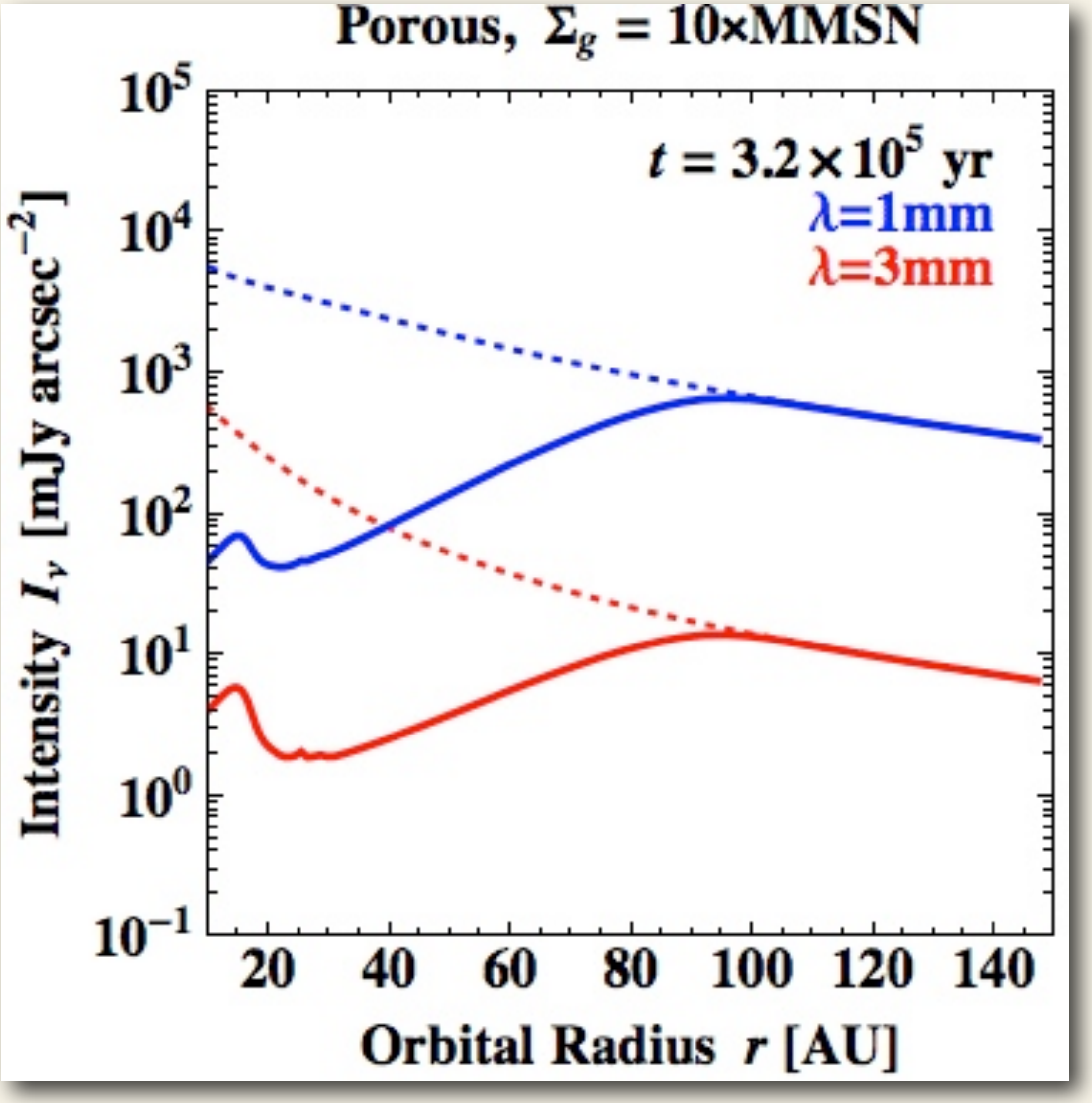
➡ Rapid Growth in the "Deep" Stokes Regime (*a* >> $\lambda_{\rm mfp}$)

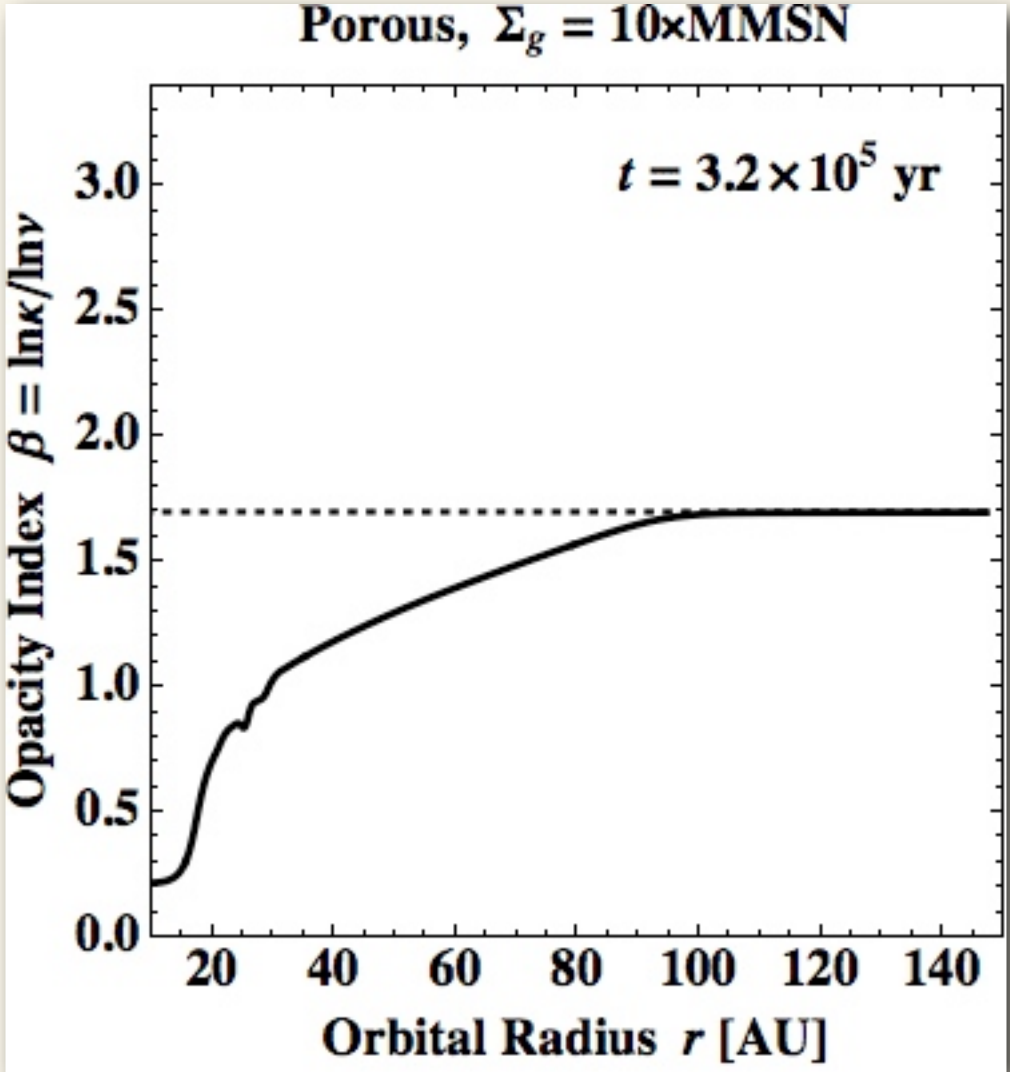
(see also Fig. 11 of Birnstiel et al. '10 and Fig. 3 of Zsom et al. '11)

Millimeter Appearance of the Stokes Acceleration

(Preliminary!)

- Σg = 10×MMSN, $(\Sigma d/\Sigma g)init$ = 0.01
- κ_ν calculated with the Maxwell-Garnett effective medium theory





Summary

- Porous aggregates grow rapidly thanks to the fast decoupling in the Stokes drag regime (***"Stokes Acceleration"***).
- **Icy planetesimals can form through direct collisional growth at <~ 10 AU.**

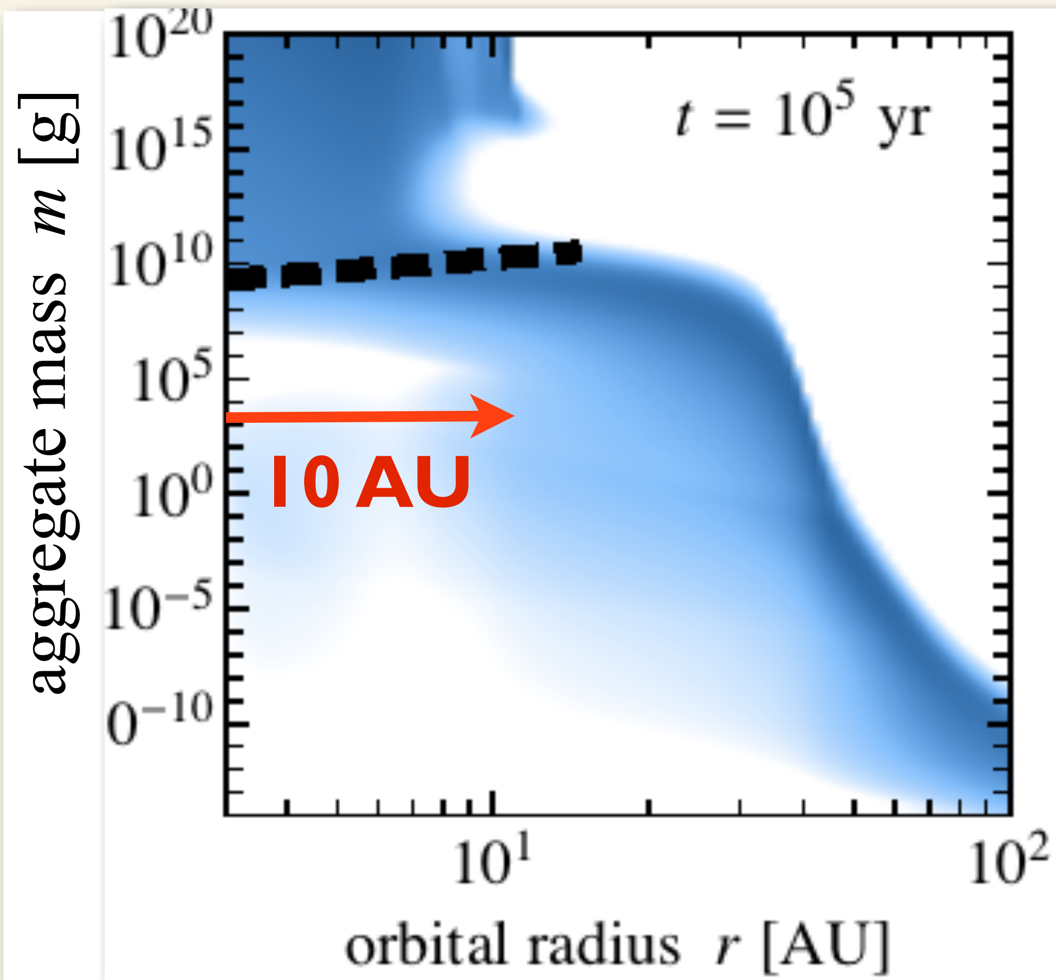
- Caveats:

• Rocky planetesimal formation is still a mystery! (Fragmentation barrier needs to be overcome.)

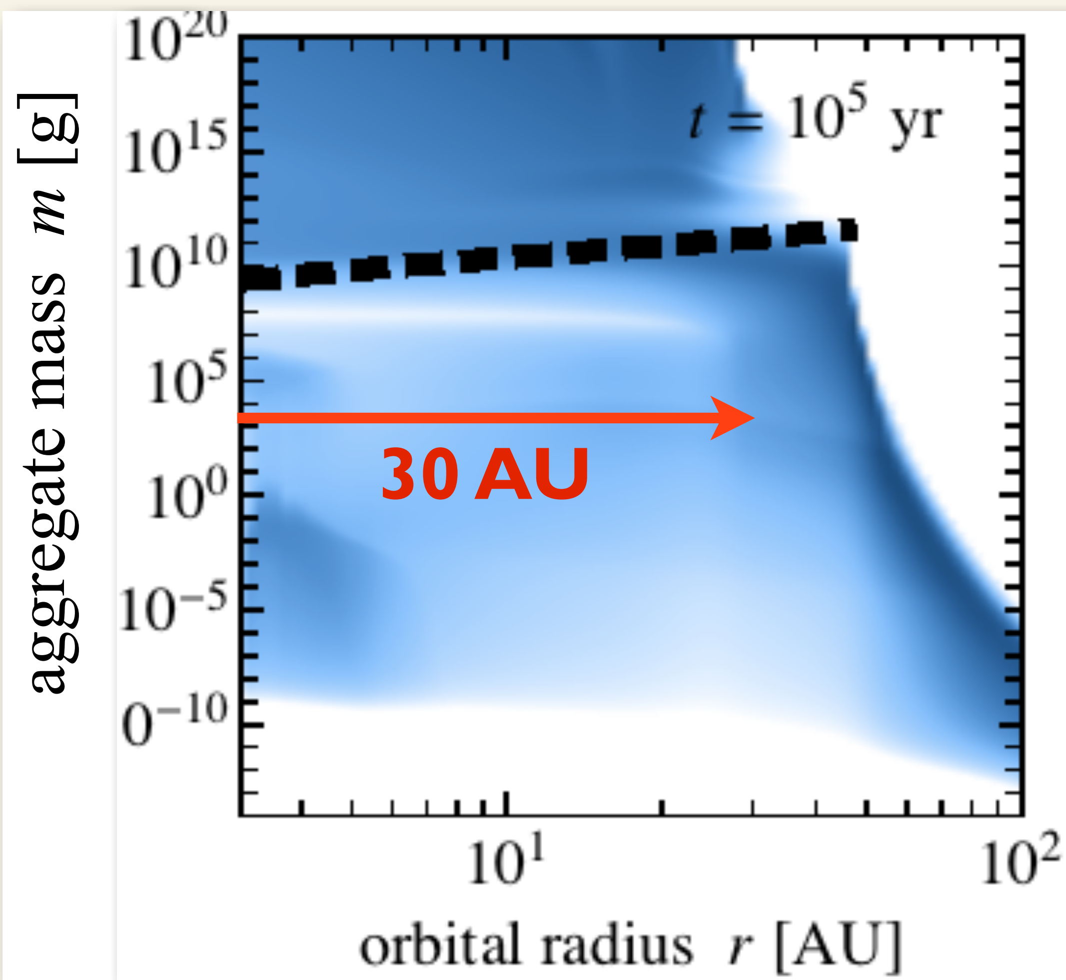
• Non-collisional compression (by headwind / self gravity) needs to be taken into account.

Disk Mass Dependence

MMSN

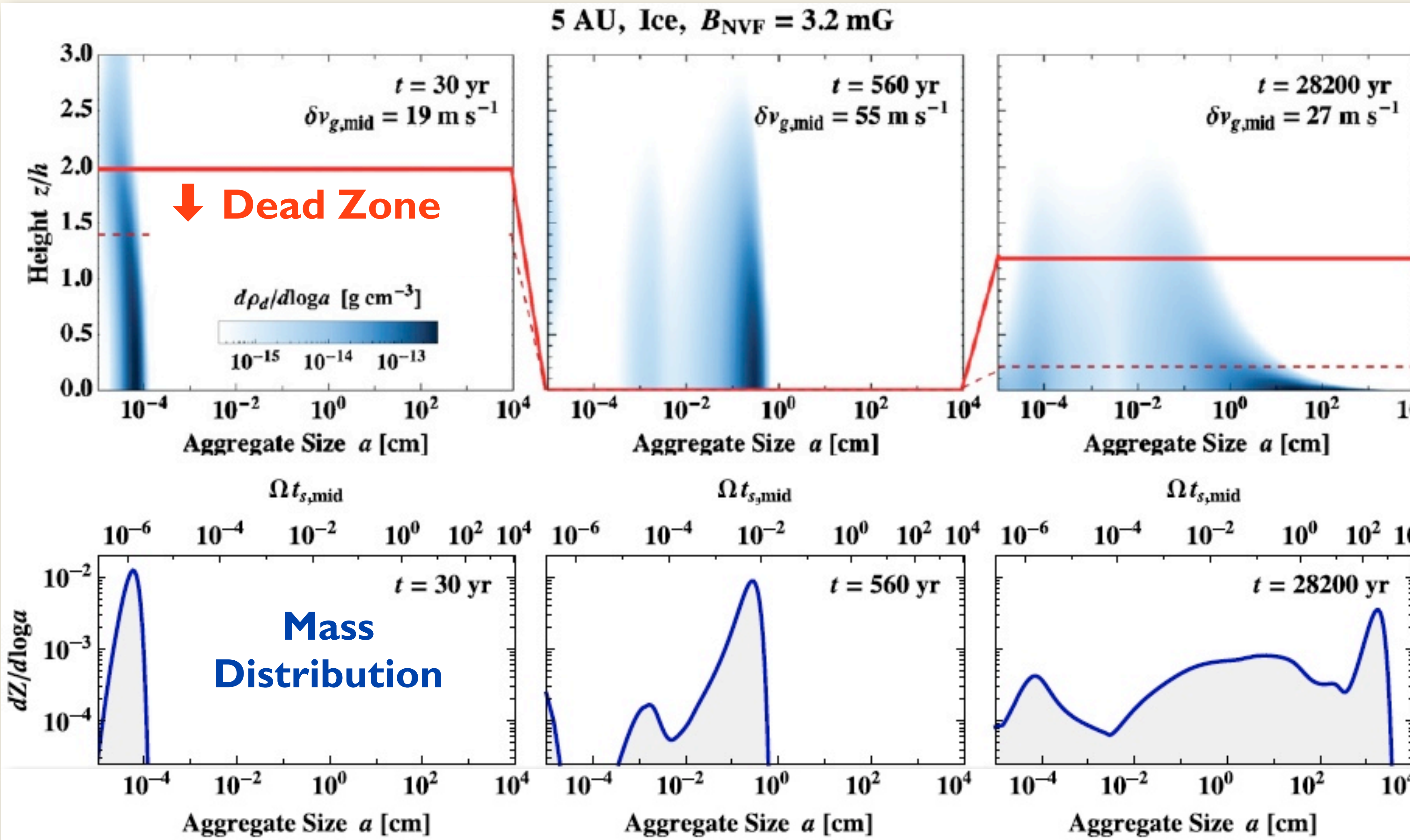


10×MMSN



Higher Σ_g → Shorter λ_{mfp} → Even Wider Stokes Region

Dust Growth in Dead Zones



(Okuzumi & Hirose 2012, ApJL, 753, L8)